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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:
Yossi Corem et al.

Application No.: 10/760,107 Confirmation No.: 7396

Filed: January 16, 2004 Art Unit: 2874

For: FIBER OPTICAL GAIN EQUALIZER Examiner: S. H. Pak

CLAIM FOR PRIORITY AND SUBMISSION OF DOCUMENTS

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

Applicants hereby claim priority under 35 U.S.C. 119 based on the following prior foreign application filed in the following foreign country on the date indicated:

Country	Application No.	Date
Israel	144434	July 18, 2001

In support of this claim, a certified copy of the said original foreign application is filed herewith.

Dated: March 2, 2006

Respectfully submitted,

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חוק הפטנטים, התשכ"ז -- 1967
PATENTS LAW, 5727-1967

בקשה לפטנט
Application for Patent

C:42225

לשימוש הלשכה
For Office Use

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אני, (שם המבקש, מענו -- ולגבי גוף מאוגד – מקום התאגדותו)
I (Name and address of applicant, and, in case of body corporate-place of incorporation)

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מבקשת פטנט from Application	*לבקשה/לפטנט to Patent/Appl.	מספר.סימן Number/Mark	תאריך Date	מדינת האיגוד Convention Country
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רצוף בזה / עוד יוגש–*יפוי כח: כללי/מיוחד P.O.A.: general / individual – attached / to be filed later -				
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C:42225

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FIBER OPTICAL GAIN EQUALIZER

XTELLUS INC.

Inventors: Sam Suh
Joseph Corem

C: 42225

FIBER OPTICAL GAIN EQUALIZER

FIELD OF THE INVENTION

The present invention relates to the field of gain equalizers using phase shift techniques in stepped substrates, especially for use in fiber optical applications.

BACKGROUND OF THE INVENTION

Gain equalizers are important components in fiber optical communication systems. One of the main functions of an optical gain equalizer is to bring all of the separate wavelength signals in a data transmission to the same amplitude, in order to optimize system spectral power budget. The functional requirements of an optical gain equalizer for use in such a system are that it should vary the intensity of the light transmitted as a function of the wavelength of the light, and without appreciably altering the spatial, temporal, or polarization distribution of the light beam.

Many types of optical gain equalizers have been described in the prior art. In US Patent No. 6,144,488, to H. Okuno, for "Optically Amplifying Device with Gain Equalizing Function", there is described a semiconductor optical amplifier, in which the gain for each wavelength is varied to provide gain equalization functionality. In US Patent No. 6,034,812, to T. Naito, for "Gain Equalizer and Optical Transmission System having the Gain Equalizer" there is described a system including three cascaded gain equalizers, the first having a maximum loss at or near the optical amplifier's peak gain, and the others having periodic loss characteristics, arranged such that they fall at or near a wavelength giving one of two gain peaks remaining when the gain characteristic of the optical amplifier the has been equalized by the first equalizer only.

In co-pending Israel Patent Application No. 142,773, hereby incorporated by reference in its entirety, there is described a multichannel gain equalizer

utilizing an array of electronically variable optical attenuators. The input optical signal, composed of a number of separate signals, each at its own characteristic wavelength. The input signal is input into a demultiplexer, which separates the individual wavelength components of the signal into n separate channels, λ_1, λ_2, λ_3, ...λ_n, one for each wavelength range. Such a demultiplexer is typically constructed of a dispersive grating. Each of these channels is input into its own variable optical attenuator, VOA_1, VOA_2, VOA_3, ... VOA_n . The levels of the signals in each channel 1, 2, 3, ...n, are detected by means of in-line signal detector elements, and a feedback signal from each detector element is used to control the level of attenuation of each VOA. The resulting signals from all of the separate channels are thus brought to the same level, and are recombined in a multiplexer unit, into a multi-channel, gain-equalized, output signal.

Though the last described gain equalizer may be simpler in design, and, when constructed on an integrated optics substrate using an array of integrated variable optical attenuators, more compact than many other prior art gain equalizers, it still consists of a significant number of components, thereby making its construction comparatively complex.

There thus exists an important need for an electronically controllable optical gain equalizer, of simple construction, which can perform spectral signal processing on an optical signal input to it, including dynamic gain equalization.

The disclosures of each of the publications mentioned in this section and in the other sections of the specification, are hereby incorporated by reference, each in its entirety.

SUMMARY OF THE INVENTION

The present invention seeks to provide a new fiber optical gain equalizer which is compact, polarization insensitive, simple in construction and operation, and of low manufacturing costs.

There is thus provided in accordance with a preferred embodiment of the

present invention, a gain equalizer consisting of a stepped transparent substrate, having part of the area of its surface stepped, and part planar. A collimated beam carrying the signal whose spectral profile is to be processed, is transmitted through this stepped substrate. The spectral profile of the signal as a function of wavelength, can be split into specific wavelength components by means of Fourier analysis. Because of the interference effects between the light transmitted through a step and that transmitted through the unstepped surface of the substrate, wavelength discrimination is produced by each step, depending on its height and area, which together determine the shape of the interference pattern obtained. A superposition of such interference patterns, each associated with one Fourier component of the spectral profile to be processed, is able to change the level of each wavelength component of the signal transmitted by the gain equalizer, and thus to process the spectral profile of the signal.

According to a further preferred embodiment of the present invention, within the optical paths of at least some of the stepped regions of the substrate, there are located phase shifting elements, each operative to change the phase of the light passing through its associated step. The phase shifting elements are electronically controllable and may preferably be liquid crystal elements. Each phase shifting element effectively adds or subtracts to the phase shift of the light passing through its associated step, and thus effectively adds tunability to the height of each step, thus enabling electronic selection of the period of the Fourier element of the signal associated with that step.

According to an additional preferred embodiment of the present invention, the phase shifting elements may be pixelated, each pixel affecting the phase of the light passing through half of the area of the associated step. When the phase difference between the pixels is such that the total phase differences between the optical paths in the two halves of the area of the associated step is 180°, destructive interference occurs, and no transmission is effected through that step. The level of transmission allowed through a given step can thus be controlled by the anti-phase components added to the optical path of the step by the pixelated phase shifting elements. The pixels thus effectively add tunability to the area of

each step, thus enabling electronic selection of the amplitude of the Fourier element of the signal associated with that step.

In accordance with a further preferred embodiment of the present invention, there is also provided an optical device including an input fiber, an output fiber, and at least one phase-shifting element disposed in part of the optical path between the input fiber and the output fiber, such that the optical interference between light in those parts of the optical path containing the at least one phase shifting element and those parts not containing the at least one phase shifting element, results in wavelength dependent transmission through the device. In this optical device, the phase shift in the at least one phase-shifting element may preferably be selected such that the optical transmission of the device has a predetermined spectral profile. The device may also preferably include a variable phase shifter controlled by means of an applied signal, in series with at least one of the at least one phase shifting elements, such that variation of the applied signal causes the predetermined spectral transmission to shift.

In accordance with still another preferred embodiment of the present invention, the at least one phase-shifting element of the above-described device includes a step in a substrate, which may also preferably have a controllable phase shifting element disposed across its optical cross section. The phase shifting element may preferably be pixelated such that it shifts the phase of light passing through at least part of the above-mentioned optical cross section of the step. In accordance with a further preferred embodiment of the present invention, the controllable phase shifting element is a liquid crystal device.

In accordance with still more preferred embodiments of the present invention, the input and the output fibers of the above-described device may be disposed such that light passes between them either by transmission or after undergoing reflection on an incorporated reflecting surface.

Alternatively and preferably, the device can incorporate a circulator and a reflecting surface, with the input and the output fibers connected to two ports of the circulator, and the reflecting surface disposed at a third port of the circulator.

Any of the above-described optical devices can, according to still more preferred embodiments of the present invention, be operative as a gain equalizer.

There is even further provided in accordance with another preferred embodiment of the present invention, an optical gain equalizer including an input fiber for inputting an input optical signal, an output fiber for outputting an output optical signal, and a substrate having at least one stepped area, disposed in the optical path between the input fiber and the output fiber.

The optical gain equalizer may preferably also include at least one variable phase shifting element, controllable by means of an applied signal, the phase shifting element being disposed across the optical cross section of the at least one stepped area of the substrate. The variable phase shifting element may preferably be pixelated such that it shifts the phase of light passing through essentially half of the cross section. The controllable phase shifting element may preferably be, in accordance with still another preferred embodiment of the present invention, a liquid crystal device.

Furthermore, in accordance with still more preferred embodiments of the present invention, the input and the output fibers of the above-described device may be disposed such that light passes between them either by transmission or after undergoing reflection on an incorporated reflecting surface.

Alternatively and preferably, the optical gain equalizer can incorporate a circulator and a reflecting surface, with the input and the output fibers connected to two ports of the circulator, and the reflecting surface disposed at a third port of the circulator.

There is further provided in accordance with still another preferred embodiment of the present invention an optical gain equalizer as described hereinabove, and also including a channel monitor, from which is obtained the applied signal according to the spectral profile of the output optical signal, such that the optical gain equalizer modifies the spectral profile of the input optical signal dynamically. In such an embodiment, the optical gain equalizer may preferably be operative to compensate for changes in the spectral profile of the input signal dynamically.

In accordance with a further preferred embodiment of the present invention, in this optical gain equalizer, the applied signal may preferably be made dependent on the effective wavelength and amplitude of that of the Fourier components of the spectral profile of the output optical signal, which is associated with the at least one stepped area of the substrate.

There is even further provided in accordance with a preferred embodiment of the present invention, a method of modifying the spectral profile of an input optical signal to a predetermined profile, including the steps of (i) determining the effective wavelengths and amplitudes of Fourier components of the spectral profile of the input optical signal, (ii) determining the effective wavelengths and amplitudes of Fourier components of the predetermined spectral profile, (iii) calculating a transfer function according to the ratio of the Fourier components of the spectral profile of the input optical signal to those of the predetermined profile, (iv) providing a substrate having a plurality of stepped areas, one stepped area for each determined Fourier component, and (v) passing the optical signal through the substrate, wherein the height of each of the stepped areas is predetermined to match the wavelength of the transfer function which is associated with its stepped area, and the area of each of the stepped areas is predetermined to match the amplitude of the transfer function associated with its stepped area.

The above-described method may also preferably include the step of providing a variable phase shifter disposed across the cross section of at least one of the stepped areas, and wherein variation of the phase shifter varies the wavelength of that component of the transfer function associated with that stepped area. In addition, the variable phase shifter may preferably be pixelated, and the generation of differential phase shifts in anti-phase by the pixels be utilized to vary the amplitude of that component of the transfer function associated with that stepped area.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description, taken in conjunction with the drawings in which:

Fig.1 illustrates schematically a stepped substrate used in the construction of a gain equalizer according to a preferred embodiment of the present invention;

Fig. 2 is a graph of transmitted light intensity as a function of wavelength, resulting from the interference of the components of an incident beam passing through the separate stepped and unstepped sections of the substrate of Fig. 1;

Fig. 3 shows the stepped substrate of Fig. 1 with the addition of a transmissive liquid crystal element in the optical path of a step;

Fig. 4 is a graph of the transmitted light intensity as a function of wavelength, as a result of the interference of components of the incident beam passing through stepped and unstepped sections of the substrate shown in Fig. 3;

Fig. 5 is a schematic illustration of the device shown in Fig. 3, but with its phase shifting element divided into separate pixels, each independently controllable by its own voltage signal applied to the electrodes of each pixel;

Fig. 6 is a graph of the transmitted light intensity as a function of wavelength, as a result of the interference of components of the incident beam passing through stepped and unstepped sections of the substrate shown in Fig. 5, when the pixels are driven such as to introduce phase shifts differing by π;

Fig. 7 is a schematic drawing of a stepped substrate similar to that of Fig. 3, but incorporating a number of steps, each of different height;

Fig. 8 is a graph showing the effect on overall transmission of the stepped substrate for each of the three steps shown in the embodiment of Fig. 7;

Figs. 9A is a schematic representation of the power spectrum of a fiber optical source of power, such as an erbium-doped fiber amplifier (EDFA);

Figs. 9B to 9D are examples of spectral profiles achievable from the input spectral profile shown in Fig. 9A, according to various preferred embodiments of the present invention;

Fig. 10 is a schematic illustration of a transmissive fiber optical gain equalizer, constructed and operative according to a preferred embodiment of the present invention;

Fig. 11 is schematic illustration of a reflective fiber optical gain equalizer, constructed and operative according to another preferred embodiment of the present invention; and

Fig. 12 is a schematic illustration of an alternative preferred signal input and output arrangement for the gain equalizer shown in Fig. 11, using a . circulator to direct the input and output signals.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is now made to Fig. 1, which illustrates schematically a stepped substrate 10, used in the construction of a gain equalizer according to a preferred embodiment of the present invention. The substrate, of total area A, is made of a transparent optical material of refractive index n. The substrate has a step 14 of area a, and of height d, projecting from the overall plane of its surface 12.

When a plane wave of light 16 of wavelength λ is projected through the substrate, then the light passing through the step undergoes a phase retardation θ, relative to that not traversing the step, given by:

$$\theta = 2\pi/\lambda \cdot (n-1)d \qquad (1)$$

The total transmitted intensity at optical infinity, of the light passing through the stepped substrate is then given by the expression:

$$I = |(A - a) + a \exp(i\theta)|^2 \qquad (2)$$

As is observed from incorporation of equation (1), the transmission is thus wavelength dependent. It is to be understood that the intensity obtained at optical infinity can be transformed to a near field plane by use of a converging lens, as will be illustrated in the complete device embodiments hereinbelow.

Reference is now made to Fig. 2, which is a graph 18 of the transmitted light intensity I obtained at optical infinity as a function of the wavelength λ of the light, resulting from the interference of the components of the incident beam

passing through the separate stepped and unstepped sections of the substrate shown in Fig. 1. The form of the graph, well-known from optical interference phenomena, arises because of the cyclic nature of the interference with phase shift, the intensity repeating itself at every additional multiple of 2π of phase difference between the interfering beams. This can be converted by means of equation (1) into wavelength dependent intensity changes. The number of periods within a given wavelength range is determined by the height of the step, the greater the height, the larger the number of periods in a given wavelength range.

The transmission modulation as a function of the phase retardation angle θ is given by:

$$T = I / |A|^2 = 1 - 2c(1-c) \cdot [\, 1 - \cos(\theta) \,] \qquad (3)$$

where $c = a/A$ is the area of the step as a fraction of the complete substrate area. The transmission modulation can vary between a value of 1, when $\theta = 2N\pi$, N being any integer, including zero in which case there is no phase retardation, and a minimum value, which can be 0 if $c = 0.5$, i.e. if the step covers half of the substrate.

Reference is now made to Fig. 3, which shows the stepped substrate of Fig. 1, in which, according to a preferred embodiment of the present invention, a transmissive liquid crystal element 20 is located in the optical path of the step 14. Though the liquid crystal element is shown adjacent to the flat bottom of the substrate, it is to be understood that it could preferably be on top of the step, or elsewhere in the optical path of the light signal passing through the step. The phase shift of the light passing through the liquid crystal element can be varied by varying the voltage V applied to the electrodes of the liquid crystal. The electrodes and their addressing leads are transparent, so as not to interfere with the optical transmission of the device. Though this preferred embodiment has been described using a liquid crystal device as the variable phase shifting device, a liquid crystal element being a convenient, low cost and widely available element, it is possible to use any alternative element, capable of applying a continuously variable phase change to the light passing through the step path, according to the voltage V applied to the phase shifter. Examples of such

elements include those based on the Faraday effect, the magneto-optical effect, the electro-optical effect, or any other suitable opto-electrical effect. Throughout this specification, whenever a liquid crystal element is thus described as being used in the construction of, or the operation of a particular embodiment of the invention, it is to be understood that the invention is not meant to be limited specifically to embodiments using a liquid crystal element for the described effect or function, but that any suitable phase shifting element can be equally well used.

Reference is now made to Fig. 4, which is a graph typical of the transmitted light intensity I obtained at optical infinity as a function of the wavelength λ of the light, as a result of the interference of the components of the incident beam passing through the two separate stepped and unstepped sections of the substrate shown in Fig. 3. When no voltage is applied to the liquid crystal device, the intensity is typically that shown in curve 22. When voltage is applied, the transmission curve 24 is shifted along the wavelength axis according to the voltage applied. A device is therefore formed, according to preferred embodiments of the present invention, whose optical transmission can be varied as a function of wavelength according to an applied voltage signal.

Reference is now made to Fig. 5, which is a schematic illustration of the device shown in Fig. 3, but wherein the phase shifting element 20 is divided preferably into two separate pixels, 26, 28, each independently controllable by its own voltage signal applied to the electrodes of each pixel. Each of the pixels have the same overall area, each intercepting half of the beam passing through the step 14. When the two pixels are driven such as to introduce into the optical paths through the step, phase shifts differing by π, destructive interference of the light passing through the step results, and the step effectively disappears. The result at optical infinity is then uniform illumination, as shown in Fig. 6, resulting from the light transmitted through the uniform remainder of the surface 12 of the substrate. The level of illumination is determined by the ratio, c, of the step with respect to the rest of the substrate, and expressed fractionally, is $(1-a/A)^2$, where a is the area of step 14, and A is the area of the remainder of the substrate 12.

When the phase shift between the two pixels 26, 28 is zero, the step behaves optically uniformly, the phase shift through it being the result of its own optical path length, and the additional phase shifts introduced by the phase shifting element 20. The resulting interference pattern at infinity is thus similar to that shown in Fig. 4. Though the embodiment illustrated in Fig. 5 shows the electrodes divided into two pixels, it is to be understood that the invention operates equally with any other number of pixels, driven such that half of the light passing through the step has a different phase shift applied to it than the other half.

A rigorous derivation of the interference effects of a single step structure in a plane substrate, with a double pixelated phase shifter is now given. The phase-shifting voltage can either be commonly applied to both pixels, hence adding a common phase shift of angle Φ to the light transmitted through the step, this phase shift being added to the phase retardation θ of the step, or alternatively, the pixels may be driven with a relative phase difference between them, φ, such that the phases in the two pixelar paths are respectively shifted by $\Phi+\varphi$ and $\Phi-\varphi$.

The total transmitted intensity at optical infinity is then given by:

$$I = \left|(A - a) + \tfrac{1}{2} a \exp[i(\theta + \Phi + \varphi)] + \tfrac{1}{2} a \exp[i(\theta + \Phi - \varphi)]\right|^2 \qquad (4)$$

where φ is the relative phase shift between the two pixelated areas of the phase shifter, and Φ is the common phase shift introduced by the two pixels working in phase. The transmission factor is now given by:

$$T = 1 - 2c + c^2(1 + \cos^2\varphi) + 2c(1-c)\cos(\theta + \Phi)\cos\varphi \qquad (5)$$

Thus the modulation can be shifted in wavelength through the commonly applied phase shift Φ added to the phase retardation θ, θ being the only phase shift angle which is wavelength dependent, or reduced in magnitude through the differential phase shift φ. Since φ arises from the phase shifting element, which is assumed to have a uniform response over the wavelength range of interest, it

does not directly affect the position of the transmission curve, only its magnitude.

Reference is now made to Fig. 7, which is a schematic drawing of the stepped substrate 30 similar to that of Fig. 3, but incorporating, according to a preferred embodiment of the present invention, a number of steps, each of different height. In the preferred embodiment shown in Fig. 7, three steps 32, 34, 36 are shown, but it is understood that the substrate may incorporate any practical number of steps, commensurate with the size of the substrate and the requirement stated hereinbelow regarding limitation of the area of the steps as a fraction of the total substrate area. Each of the steps produces a different interference effect of the incident light 16 passing through that step with the light passing through the unstepped portions 12 of the substrate. Beneath each step is located a pixelated controllable phase shifting device, 37, 38, 39.

The effect on the overall transmission curve of the stepped substrate for each of the three steps shown in the embodiment of Fig. 7 is illustrated in the graph shown in Fig. 8. Each of the steps of Fig. 7, having a different height, results in a different transmission modulation characteristic, and the curves are labeled, 32a, 34a and 36a, according to the labeling of the steps which result in them. When the step is large, such as step 34, there are a large number of periods of the transmission modulation curve 34a within each wavelength range, whereas when the step is small, such as step 36, one cycle of the modulation function 36a, may extend over a wide wavelength range. Furthermore, as explained above, the positions of each of the curves can be independently shifted along the wavelength scale by application of common phase shifts to both pixels of the relevant pixelated phase shifting units 37, 38, 39. As further explained hereinabove, the unperturbed amplitude of each curve is dependent on the area of the step associated with that curve, as a fraction of the unstepped area. When a differential phase shift is applied to the two pixels under a given step, the effect of each of the pixels in association with their sections of the step, results in curves of equal amplitude but shifted relative to each other according to the differential phase shift applied to the pixels. Vector addition of these two curves results in one curve, equivalent to that of the unperturbed step, whose amplitude

is dependent on the differential phase shift applied, and which can be independently reduced from its maximum value to zero as the differential phase shift is varied from zero to π.

The stepped substrate device shown in Fig. 7 can thus be used to construct a transmissive optical component having a desired spectral transmission function, by selection of the substrate steps of the correct predetermined height and surface area, and, if necessary, by the application of the correctly selected additional phase shifts by means of the controllable phase shifting elements. The superposition of the interference curves from all of the predefined steps thus builds a predefined transmission curve as a function of wavelength. Such a process is equivalent to the construction of the curve from its Fourier components, with the wavelength of each Fourier component being determined by the effective height of each step, and the amplitude of each Fourier component being determined by the effective area of each step. The transmission curve can be represented mathematically as the transfer function between the Fourier transforms of the input and the output optical signals, and is expressed as the division of the Fourier components of the two optical signals, as functions of their wavelength and amplitude. The terms effective height and effective area are used to respectively describe the physical height and area of the steps, as amended phase-wise by the application of voltages to the phase shifting elements.

In practical application, the areas of the steps must be kept small to ensure that cross-terms resulting from interference between steps, rather than interference between the steps and the unstepped substrate, be kept to a minimum. Furthermore, the unstepped area should be kept large, to ensure an adequate transmission level when all of the steps are cancelled by setting their phase shifter pixels to provide antiphase transmission through each step.

Reference is now made to Fig. 9A, which is a schematic representation of the power spectrum of a source of optical power, such as, for instance, an erbium-doped fiber amplifier (EDFA), as commonly used as the source of power in C-band fiber optical communications systems. The example of the output of an

EDFA is used in this specification to illustrate some of the applications in the field of optical signal amplitude processing, of devices constructed and operative according to various preferred embodiments of the present invention. In such communications systems, it is often necessary to perform power adjustment operations on the output signals. It is to be understood though, that the EDFA output signal applications are used only as examples of the capabilities of preferred devices according to the present invention, and that the invention is equally applicable to other sources and other wavelength ranges of operation.

Power leveling, to optimize the spectral power budget within the system, is a common operation used in power level management in optical communication systems, and a gain equalizer is used to perform this operation. The spectral transmission characteristics of an optical communications link can be affected by many factors, both long term and short term. In general, each EDFA unit produced, even from the same production batch, may have a slightly different power spectrum and may have different input characteristics as a function of power input and wavelength. Consequently, changes in the amplitude or wavelength of the input signal to the EDFA, changes in environmental conditions, and also longer term changes arising from aging of the amplifier can cause the spectral characteristics of the output optical signal to change dynamically. Therefore, the gain equalizer must be capable of dynamic adjustment to adapt itself to the initial and to the changing characteristics of each EDFA, and to changes in the transmission characteristics.

The characteristic power spectrum obtained at the EDFA output, as typically shown in Fig. 9A, can be Fourier analyzed in order to extract the Fourier components of the curve, including their wavelengths and amplitudes. These components can then be used in order to construct a transmissive optical component, such as that shown in Fig. 7, wherein each of the steps is operative to simulate the effect of one of the Fourier components of the EDFA power spectrum. According to a first preferred embodiment of the present invention for use in this application, the steps are constructed to approximately flatten the spectral profile of the source, according to the average profile obtained. Fine

tuning is then applied by adjustment of the control signals on the pixelated phase shifters associated with each step, in order to obtain a better level of flattening, and thus to compensate for the minor changes between different EDFA's and their operational conditions. The limit of the flatness achievable is on the number of steps used in the gain equalizer. The result of this process is shown in the typical spectral profile schematically displayed in Fig. 9B.

According to another preferred embodiment of the invention, the gain equalizer can be dynamically tuned, by adjustment of the control signals on the pixelated phase shifters associated with each step. The adjustment is made in accordance with a feedback signal obtained from channel power monitoring, in order to determine in which wavelength regions the output is changing, and by how much. In this way, it is possible to compensate for changes in the spectral profile due to operational or environmental changes. The output of the EDFA, after passage through the gain equalizer, can thus be maintained effectively flat at all times.

According to yet another preferred embodiment of the invention, when the pairs of pixels on every step are driven in antiphase, the component does not introduce spectral changes to the EDFA output, but simply reduces the output uniformly across its spectrum. When the beams through each of the halves of each step are all in anti-phase, then the attenuation is at a maximum, as defined by the insertion loss of the device. The component can thus be used as a wavelength independent attenuator. A typical example of the output of such a component is shown schematically in Fig. 9C, which should be compared with the input spectrum of Fig. 9A.

According to another preferred embodiment of the invention, the control voltages applied to the phase shifting elements are adjusted to be such as to enable the synthesis of a predefined spectral profile. This application is useful for generating power spectra which precompensate for the spectral response of the system into which they are working. Thus, for instance, if it is known that higher frequencies are attenuated in a certain transmission network, it is possible using this preferred embodiment to taper the power profile to provide more power

output at the high frequency end of the wavelength range used. Such an output profile is illustrated in the typical spectral power profile shown in Fig. 9D.

Reference is now made to Fig. 10, which is a schematic illustration of a fiber optical gain equalizer, constructed and operative according to a preferred embodiment of the present invention. The gain equalizer utilizes a stepped transmissive substrate 50, which can preferably be made of glass or quartz to provide mechanical and optical stability. The number of steps 52, and their heights and areas are selected according to preferred methods of the present invention as described hereinabove. A liquid crystal element 54 is disposed, preferably close to the non-stepped face of the substrate, and may be attached thereto adhesively for stability and ease of construction. Separate pixelated electrodes 56 are applied to the liquid crystal element at locations opposite the steps, the pixels of each separate electrode being of essentially equal area. Change of the control voltages on the pixelated electrodes causes changes in the phase of the light transmitted through the steps, in the same way as described hereinabove. The electrodes and their address leads are constructed of a transparent conductive material, as is known in the art, to avoid interference with the optical transmission through the device.

The optical signal is input to the gain equalizer through a fiber 58, which terminates in a GRIN lens rod 60, which outputs the optical signal as a collimated beam 62. Alternatively and preferably, the input fiber can terminate in free space, and the beam diverging therefrom be collimated by means of a positive lens 64. This alternative input arrangement is shown in dotted outline in Fig. 10. After traversing the stepped substrate assembly, the amplitude processed beam of collimated light 66 is refocused into the output fiber 68 by means of another GRIN rod lens 70, or by means of a free space lens 72. The use of a collimating element, whether a free-space lens or a GRIN rod lens, enables the interference pattern generated at optical infinity by the beam passing through the stepped and the unstepped parts of the substrate, to be correctly input to the output fiber 68.

The signal passing down the output fiber is sampled, preferably by means

of a directional coupler 74, and the spectral content of the signal determined preferably using a channel power monitor 76. The signals from this channel power monitor are passed to a processing unit 78, where the levels of each of the selected Fourier wavelength components of the actual output beam are compared with those of the desired output beam spectral profile. The required feedback control signals are then generated for driving the pixelated electrodes of the liquid crystal element such that the output of each channel reaches its desired level. The feedback signal incorporates information for correcting the amplitude and comparative phase of each of the selected Fourier wavelength components of the output signal to achieve the desired spectral profile. Some of the various types of output spectral profiles that can be achieved have been illustrated and explained in connection with Figs. 9B to 9D.

According to further preferred embodiments of the present invention, the signal sampling can be performed anywhere in the optical communications channel where the power level is to be monitored. The signal monitoring can even be performed remotely from the gain equalizer, such as at the receiver station or at an en-route repeater unit, either of which could be at a considerable distance from the gain equalizer itself. In this way, the gain equalization is performed on the basis of the signal strengths of each channel detected at the destination point of the signal, where gain equalization is important for optimizing the system power budget.

The embodiment of this invention illustrated in Fig. 10 is a transmissive gain equalizer. Reference is now made to Fig. 11, which schematically illustrates a gain equalizer, according to another preferred embodiment of the present invention, but in which the light is reflected through the stepped substrate. In this case, the optical path difference through the steps is doubled, since the light passes twice down the length of each step, and the step heights can therefore be halved in comparison with the transmissive embodiment shown in Fig. 10.

In Fig. 11, the input fiber is connected to one fiber of a dual fiber collimator 84, which converts the signal into a collimated beam 86. The dual fiber collimator 84 may either be a GRIN rod component, as shown in Fig. 11,

or it may be implemented in a free space embodiment using the two ends of the input and output fiber positioned at the focal plane of a collimating lens, in a similar manner to the dotted embodiment shown in Fig. 10. The beam preferably passes through the liquid crystal element 88 with transparent pixelated electrodes 90 attached thereto for spatially controlling the phase shift applied to the light passing through. In this reflective embodiment, the stepped substrate can take a number of alternative forms. According to the simplest preferred form, as shown in Fig. 11, the stepped substrate 92 need not be transparent since the substrate has a reflective layer 94 on its top side, which covers both the steps themselves, and the remaining unstepped surface of the substrate, such that the light does not even enter the substrate. The stepped substrate thus acts as a stepped mirror, reflecting the light back from the substrate down different path lengths in the air spaces between the liquid crystal device and the mirror steps. It is thus the air spaces, with their unity refractive index, which must be used in calculating the interference resulting from the phase shifts engendered by the stepped structure. The advantage of this embodiment is that the stepped substrate can be constructed of a molded material, such as a stable epoxy material, or a suitable thermosetting plastic, with the concomitant savings in construction cost over a precision ground glass or quartz substrate.

According to a further preferred embodiment, the substrate can be a transmissive element, similar to that used in the previously shown embodiments in this specification, and the reflective coating applied to the smooth bottom surface of the substrate. In this case, the calculation of the phase shifts from the steps is similar to that of the transmissive embodiments, except for the halving of the step heights as previously mentioned.

The reflected intensity processed collimated beam is output from the gain equalizer through the second fiber 82 of the dual beam collimator. The signal channel monitoring means, and the way in which the different wavelength channel signals are used to control the phase shifter pixels are essentially similar to those described in the transmissive embodiment of Fig. 10.

Reference is now made to Fig. 12, which is a schematic illustration of an

alternative preferred signal input and output arrangement for the gain equalizer shown in Fig. 11. According to this preferred embodiment, a circulator 100 is used to direct the input signal from the input fiber 102 to the equalizer port 104, and the reflected processed signal from the equalizer port 104 to the output fiber 106. In the embodiment shown in Fig. 12, a collimating lens 108 is preferably used to configure the input beam for transmission through the stepped substrate from the beam issuing from the end of the circulator output port fiber 104, in a similar manner to the embodiment shown in dotted outline in Fig. 10.

The devices described in the above-mentioned preferred embodiments of the present invention, have been directed at applications where dynamic control of the spectral properties of the light signals transmitted the device is desired, such as in a dynamic gain equalizer. For this purpose, variable controllable phase-shifting elements are incorporated in at least some of the stepped optical paths. According to a further preferred embodiment of the present invention, there is provided a static spectral optical profiler, in which the spectral properties of the incoming signal are amended in a predetermined and fixed manner. Such a device is shown, in its simplest form, in Fig. 1, with a single stepped substrate. More complex examples are shown in any of the multi-stepped substrate embodiments described elsewhere in this specification, such as in Figs. 7, 10 and 11, but with the absence of the variable phase shifting elements. The spectral modifying characteristics of such a device may be used, for instance, to construct a fixed gain equalizer, useful for flattening the output of devices with a peaked or otherwise undesirable spectral profile. Such spectral adjustment is typically performed currently with a static filter or filters. The static spectral profiler according to this preferred embodiment of the present invention provides an alternative device to a filter, which is of low construction cost, is very stable in its properties and may be of low insertion loss. The stability arises from the fact that the properties of the device are dependent only on the dimensions of the substrate, and the value of its refractive index, both of which can be very stable. The construction costs can be particularly low if the profile modifier is of the reflective type as described hereinabove, and is preferably constructed of a

molded transparent epoxy or another plastic material, with a reflective coating on the rear surface.

In all of the above-described embodiments, the stepped substrate of the gain equalizer operates in an essentially polarization independent manner, since a birefringent substrate material would not generally be used. However, the phase shifting elements associated with each step may have polarization dependence. If these elements are, for instance, liquid crystal devices, then it is possible to eliminate any polarization dependence arising from these elements by any of the methods described in co-pending Israel Patent Application No. 142,773.

It is appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

CLAIMS

We claim:

1. An optical device comprising:

an input fiber;

an output fiber; and

at least one phase-shifting element disposed in part of the optical path between said input fiber and said output fiber, such that the optical interference between light in those parts of said optical path containing said at least one phase shifting element and those parts not containing said at least one phase shifting element results in a wavelength dependent transmission through said device.

2. An optical device according to claim 1 and wherein the phase shift in said at least one phase-shifting element is selected such that the optical transmission of said device has a predetermined spectral profile.

3. An optical device according to claim 2 and also comprising a variable phase shifter controlled by means of an applied signal, in series with at least one of said at least one phase shifting elements, such that variation of said applied signal causes said predetermined spectral transmission to shift.

4. An optical device according to any of claims 1 to 3, wherein said at least one phase-shifting element comprises a step in a substrate.

5. An optical device according to claim 4, wherein said at least one step in said substrate has a controllable phase shifting element disposed across its optical cross section.

6. An optical device according to claim 5, wherein said phase shifting element is pixelated such that it shifts the phase of light passing through at least part of said cross section.

7. An optical device according to claim 5, wherein said controllable phase shifting element is a liquid crystal device.

8. An optical device according to any of claims 1 to 7 wherein said input fiber and said output fibers are disposed such that light passes by transmission between them.

9. An optical device according to any of claims 1 to 7, and also comprising a reflecting surface, and wherein said input fiber and said output fibers are disposed such that light undergoes reflection between them.

10. An optical device according to any of claims 1 to 7 and also comprising a circulator and a reflecting surface, and wherein said input fiber and said output fibers are connected to two ports of said circulator, and said reflecting surface is disposed at a third port of said circulator.

11. An optical device according to any of claims 1 to 10, and operative as a gain equalizer.

12. An optical gain equalizer comprising:

an input fiber for inputting an input optical signal;

an output fiber for outputting an output optical signal; and

a substrate having at least one stepped area, disposed in the optical path between said input fiber and said output fiber.

13. An optical gain equalizer according to claim 12, and also comprising at least one variable phase shifting element, controllable by means of an applied signal, said phase shifting element being disposed across the optical cross section of said at least one stepped area of said substrate.

14. An optical gain equalizer according to claim 13, and wherein said variable phase shifting element is pixelated such that it shifts the phase of light passing through essentially half of said cross section.

15. An optical gain equalizer according to either of claims 13 and 14, wherein said controllable phase shifting element is a liquid crystal device.

16. An optical gain equalizer according to any of claims 12 to 15 wherein said input fiber and said output fibers are disposed such that light passes by transmission between them.

17. An optical gain equalizer according to any of claims 12 to 15, and also comprising a reflecting surface, and wherein said input fiber and said output fibers are disposed such that light undergoes reflection between them.

18. An optical gain equalizer according to any of claims 12 to 15, and also comprising a circulator and a reflecting surface, and wherein said input fiber and said output fibers are connected to two ports of said circulator, and said reflecting surface is disposed at a third port of said circulator.

19. An optical gain equalizer according to any of claims 13 to 18, and wherein said applied signal is obtained from a channel monitor according to the spectral profile of said output optical signal, such that said optical gain equalizer modifies the spectral profile of said input optical signal dynamically.

20. An optical gain equalizer according to claim 19, and wherein said optical gain equalizer compensates for changes in the spectral profile of said input signal dynamically.

21. An optical gain equalizer according to claim 19, and wherein said applied signal is dependent on the effective wavelength and amplitude of that of the Fourier components of the spectral profile of said output optical signal, which is associated with said at least one stepped area of said substrate.

22. A method of modifying the spectral profile of an input optical signal to a predetermined profile, comprising the steps of:

determining the effective wavelengths and amplitudes of Fourier components of the spectral profile of said input optical signal;

determining the effective wavelengths and amplitudes of Fourier components of said predetermined spectral profile;

calculating a transfer function according to the ratio of said Fourier components of the spectral profile of said input optical signal to those of said predetermined profile;

providing a substrate having a plurality of stepped areas, one stepped area for each determined Fourier component; and

passing said optical signal through said substrate;

wherein the height of each of said stepped areas is predetermined to match the wavelength of said transfer function which is associated with said stepped area, and the area of each of said stepped areas is predetermined to match the amplitude of said transfer function associated with said stepped area.

23. The method of claim 22 and also comprising the step of providing a variable phase shifter disposed across the cross section of at least one of said stepped areas, and wherein variation of said phase shifter varies the wavelength of that component of said transfer function associated with said stepped area.

24. The method of claim 22 and wherein said variable phase shifter is pixelated, and wherein the generation of differential phase shifts by said pixels varies the amplitude of that component of said transfer function associated with said stepped area.

For the applicant:

Sanford T. Colb & Co.
Advocates and Patent Attorneys
C: 42225

FIG. 1

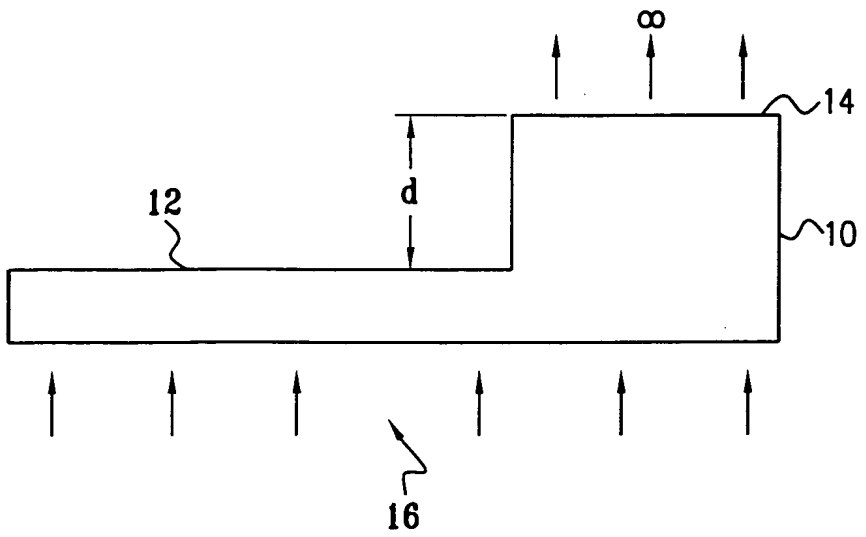


FIG. 2

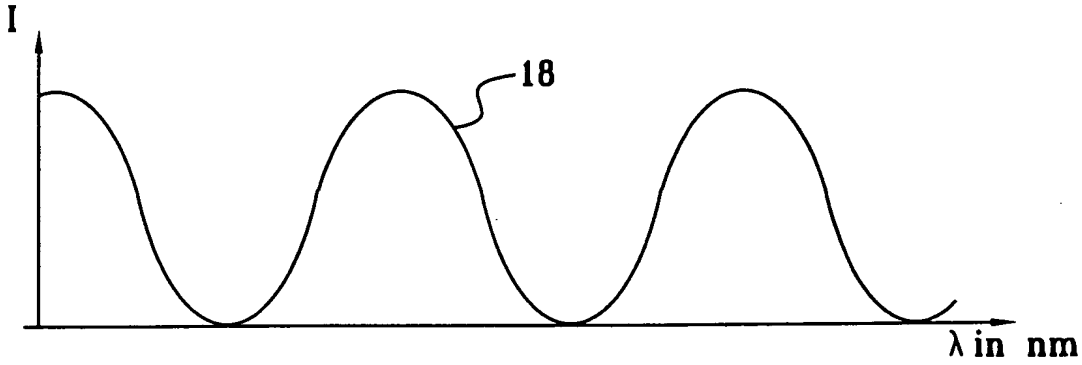


FIG. 3

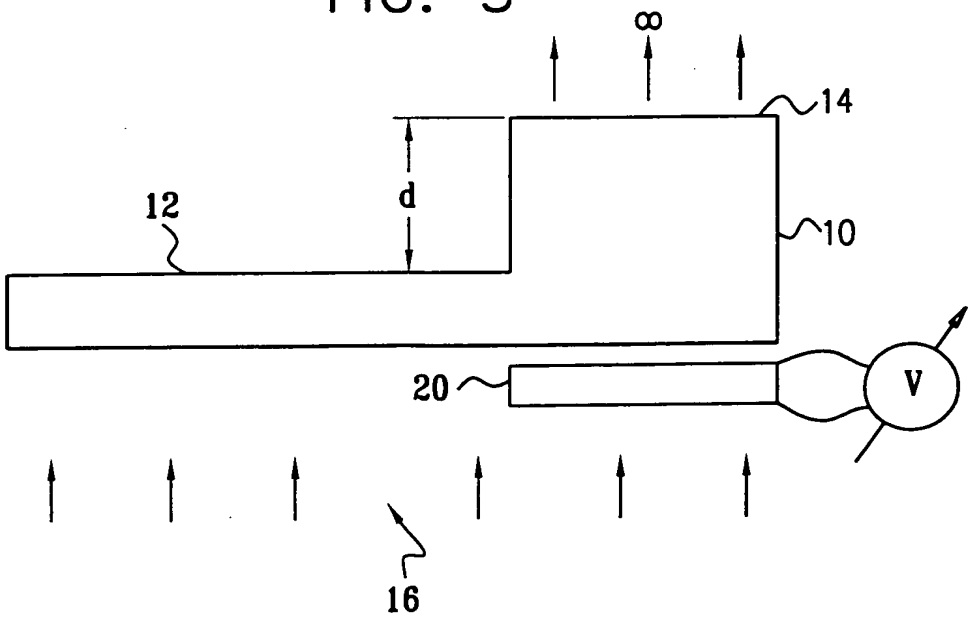


FIG. 4

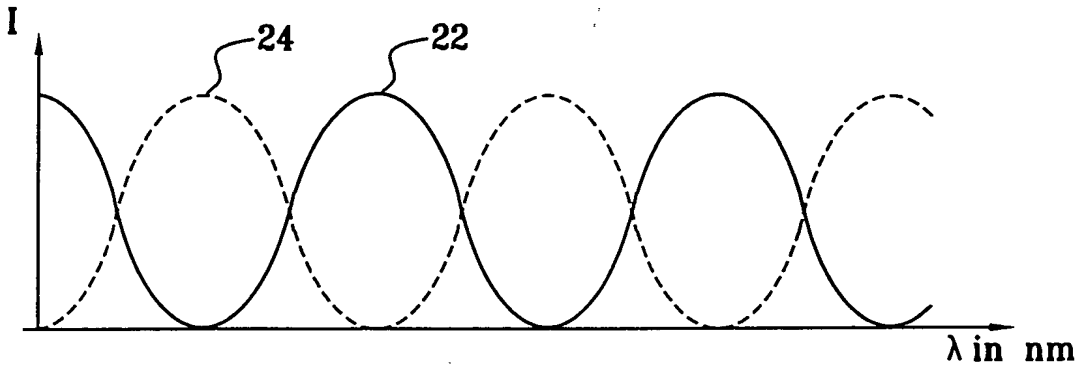


FIG. 5

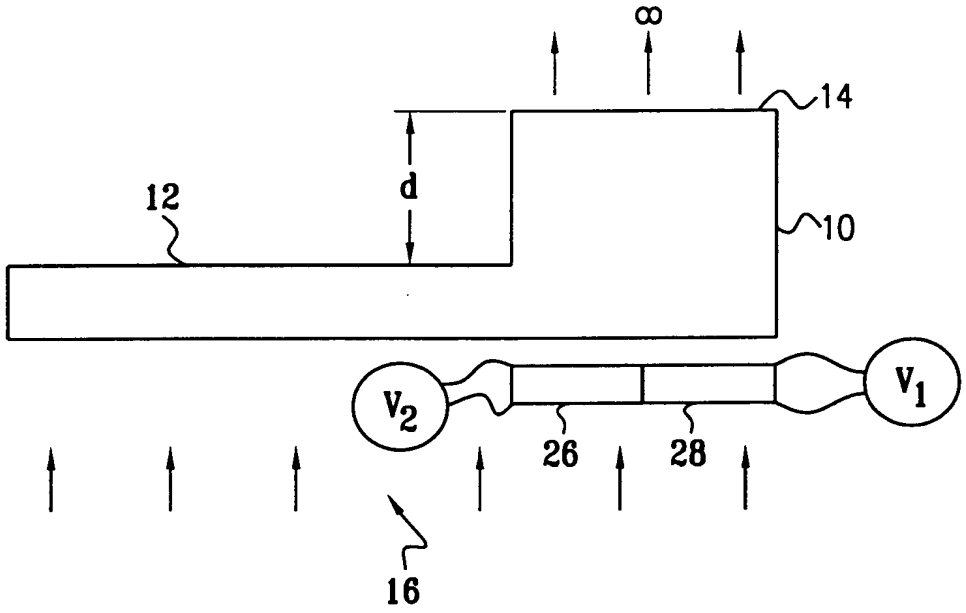


FIG. 6

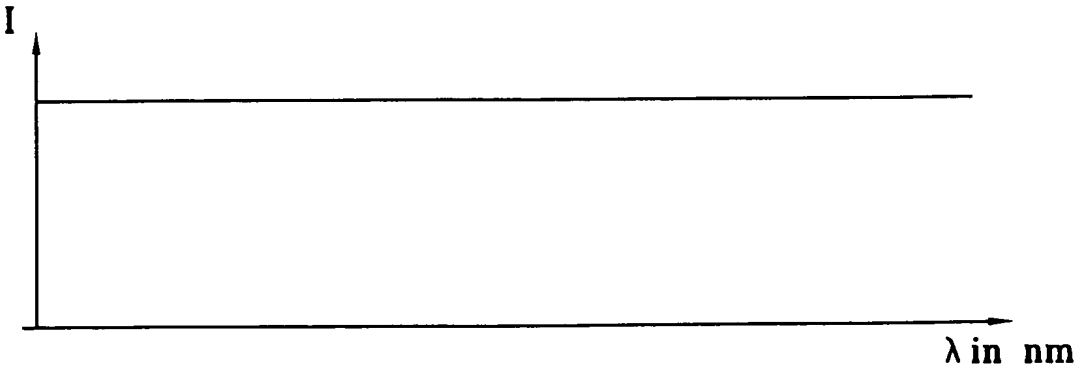


FIG. 7

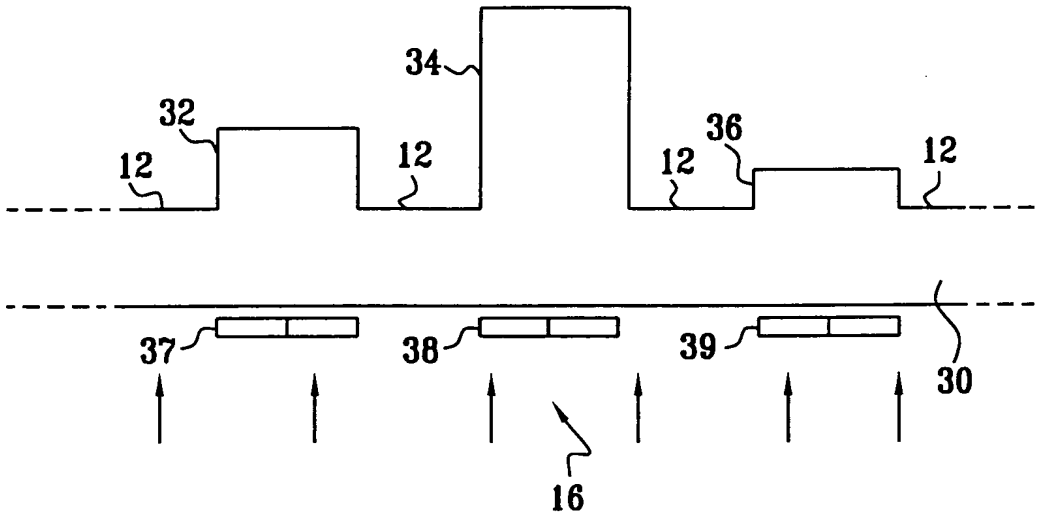
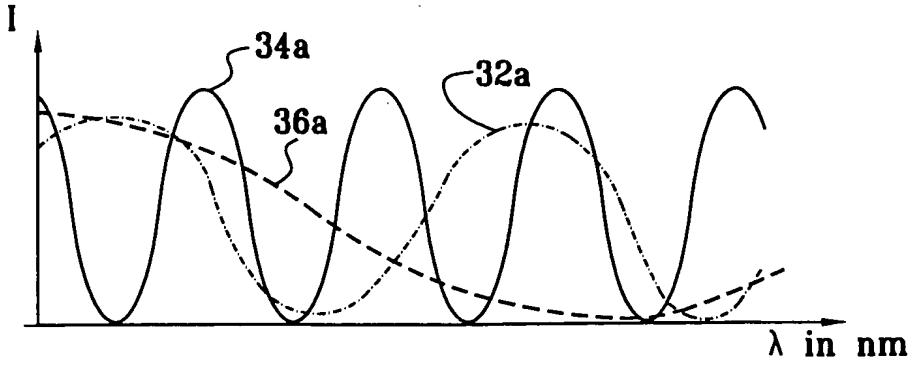


FIG. 8



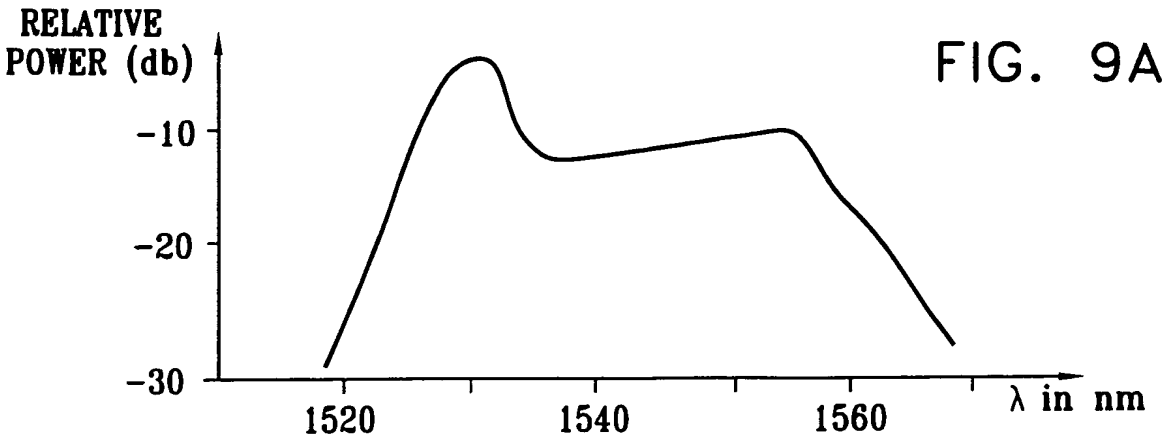


FIG. 9A

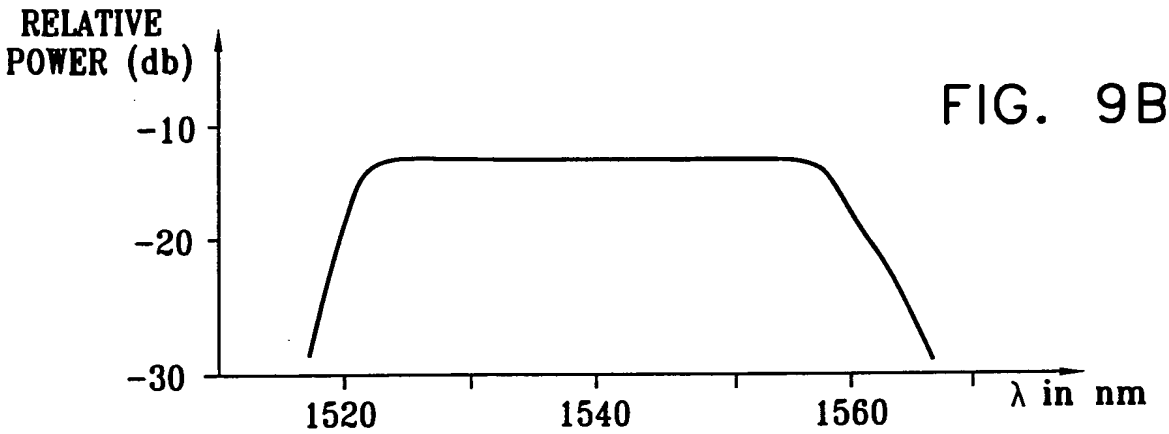


FIG. 9B

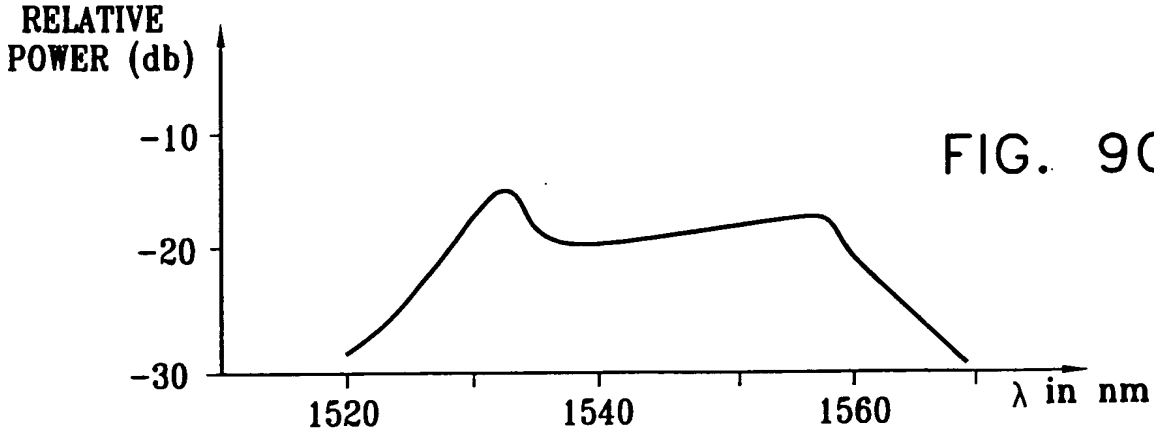


FIG. 9C

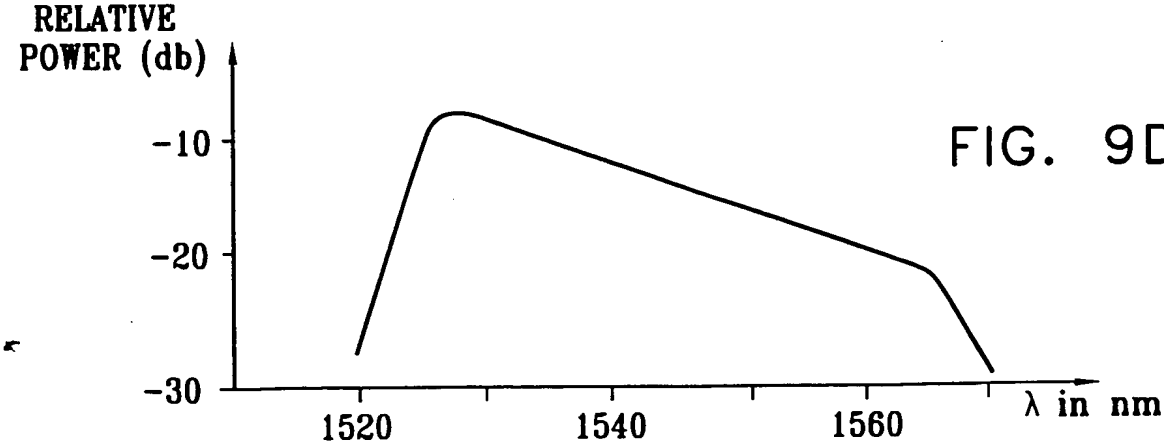


FIG. 9D

FIG. 10

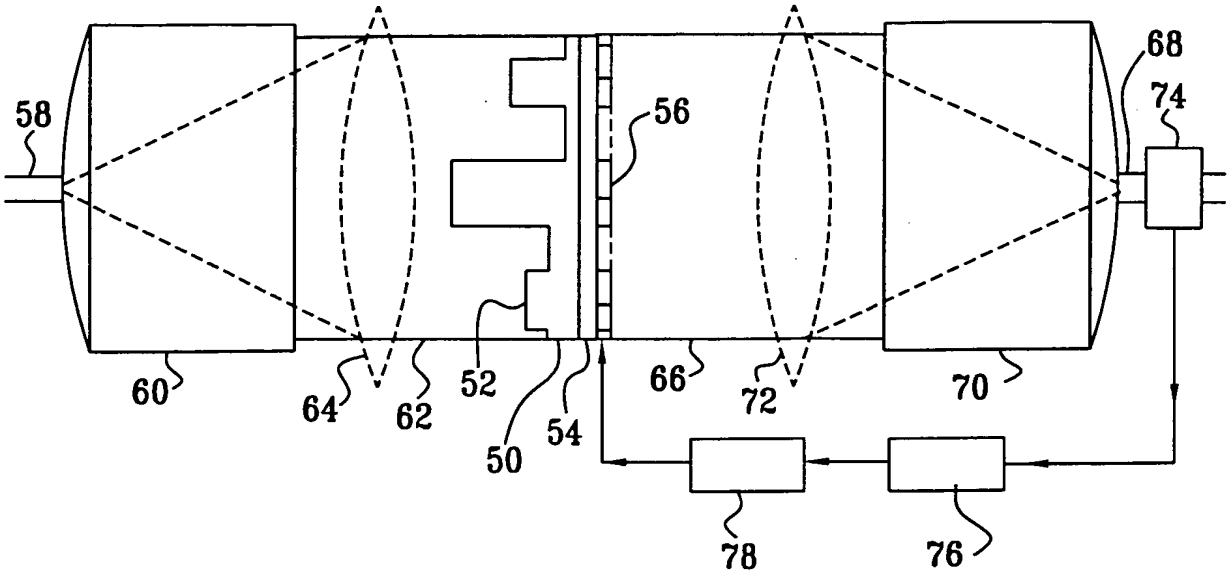


FIG. 11

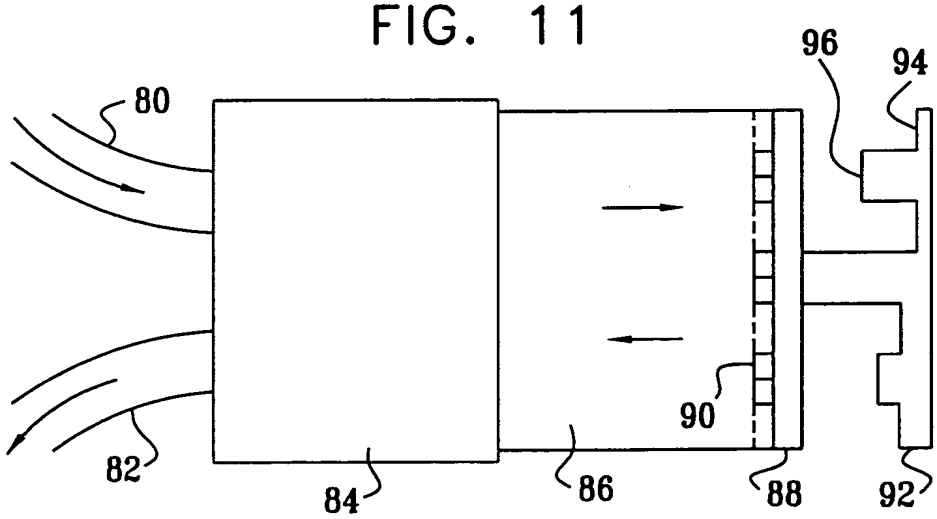
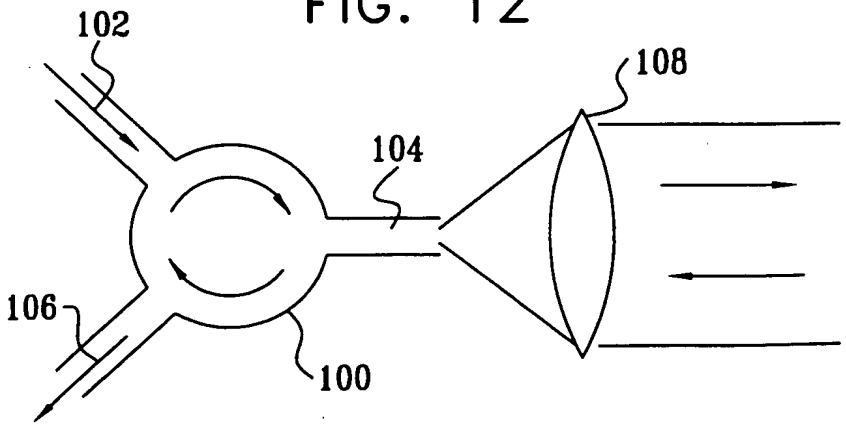


FIG. 12



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תאריך: 19.1.06

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ג.נ.,

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משווה הגברה עבור סיבים אופטיים
<u>מספרנו: 42225</u>

בהתאם לבקשתך מיום 25.12.05, מצורף בזה מסמך בכורה של הבקשה המצוינת מעלה.

כמו כן, מצורף בזה חשבוננו.

בכבוד רב,

ענת חכמין
סנפורד ט. קולב ושות'